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The Dynamic Response of Thick-Liquid Shielding in Z-IFE Reactors

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***Abstract*—A major concern in the design of thick-liquid protected inertial fusion reactors of all types is the dynamic response of the shielding liquid to the pulsed explosions. Induced liquid motion can stress and damage solid chamber structures such as the first-wall. In a z-pinch based inertial fusion (Z-IFE) reactor this issue becomes particularly critical due to the relatively large proposed target yields of several GJ. In this paper we summarize an analysis of the liquid response taking into account ablation of target facing surfaces, pocket venting, and neutron isochoric heating. The impact of varying several reactor parameters is also discussed.**

Keywords-fusion; z-ife; flibe

I. INTRODUCTION

In Z-IFE reactor designs, the fusion explosion is surrounded by a flowing curtain of the molten salt flibe to shield the solid chamber structures from x-rays, ionized debris, and neutrons. A potential cross-section of this curtain is shown in Fig. 1.

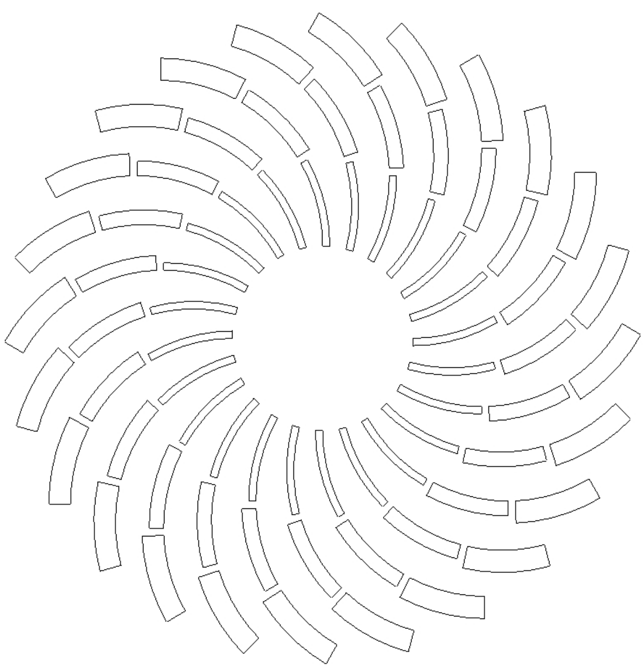

Figure 1. The cross-section of an "enhanced venting" curtain composed of arcing slab jets.

There are three phenomena will that lead to outward motion of the liquid curtain: x-ray ablation of target facing surfaces, form drag on the curtain as vapor vents from the central pocket, and jet breakup due to neutron isochoric heating. This induced outward motion could cause threatening mechanical stresses if the curtain liquid were to impact the first-wall. It is, therefore, important to understand and quantify the dynamic response of thick-liquid shielding in Z-IFE reactors so that the chamber can be designed to avoid such impacts.

The liquid shielding geometry called for in Z-IFE is quite similar to the concepts employed in both the HYLIFE [1] and HYLIFE-II [2] reactor studies. Consequently, much of the analysis previously carried out to understand the dynamics of these chambers can be reapplied. In the sections that follow, we detail qualitatively and quantitatively how each process listed above contributes to the outward motion of the liquid curtain and apply the results to Z-IFE reactor conditions.

II. LIQUID ABLATION

About 30% of the energy released from a Z-IFE target will be in the form of x-rays and ionized debris. This energy will deposit in and ablate a thin layer of liquid from all target facing surfaces. This event will apply a strong impulse to the underlying liquid and induce liquid motion toward the first-wall as the ablated plasma rockets toward the center of the chamber.

The first step in quantifying the impulse that will be delivered is to calculate the mass of flibe that will be ablated (m_a). Pocket geometry and fusion yield determine the x-ray flux that is delivered to the target facing surfaces. A typical fusion x-ray spectrum will produce the ablation depths given in Fig. 2 [3]. Ablation mass can then be determined by multiplying the appropriate ablation depth and the surface area of the directly exposed inner pocket (A).

Taking E_{xi} to be the total target yield in the form of x-rays and ionized debris minus the energy needed to vaporize, disassociate and ionize the ablated flibe, the specific ablation impulse (I) can be shown to be

$$I = \frac{\sqrt{2 \cdot m_a \cdot E_{xi}}}{A}.$$

Dividing this by the aerial density of the shielding curtain (μ, the amount of mass for each unit of target-facing surface area) gives the average outward speed induced from liquid ablation (v_a) to be

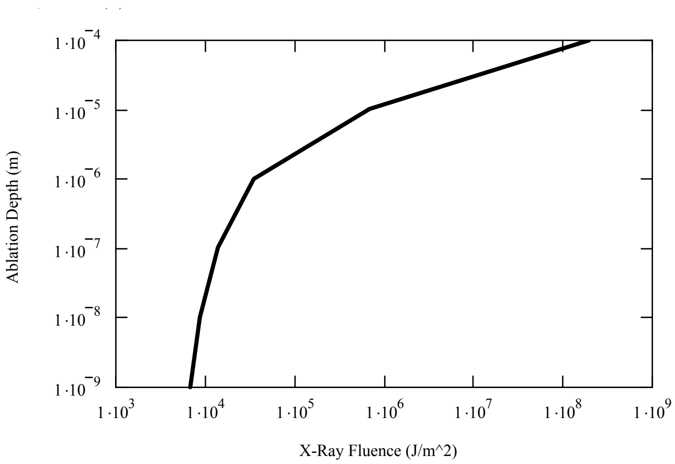

Figure 2. Ablation depth in flibe as a function of x-ray fluence for a typical fusion spectrum.

$$v_a = \frac{I}{\mu}.$$

III. Pocket Venting

After the initial x-ray ablation has occurred, the plasma generated will cool by re-radiating to newly exposed target facing liquid surfaces and vaporizing more flibe. This vapor will then impose a form drag on the liquid curtain as it vents through it over some period of time, thus generating another impulse that will further accelerate the liquid shielding outward.

If the vaporized shielding is assumed to equilibrate at a temperature of 5000 K before venting begins, 57% of E_{xi} will be used in heating the flibe to its boiling point and inducing its phase change to vapor. The remaining 43% will go into generating an initial central pocket pressure of

$$P_0 = \frac{0.43 \cdot E_{xi} \cdot (\gamma - 1)}{V},$$

where γ is the specific heat ratio of the vapor and V is the volume of the pocket. The amount of additional induced speed from venting (v_v) will be

$$v_v = \frac{P_0 \cdot \tau}{\mu},$$

where τ (the venting time constant) is a function of the vapor sound speed, the pocket volume, and the curtain venting area.

IV. Neutron Isochoric Heating

Glenn [4] has studied the mechanisms by which volumetric deposition of neutrons will impart bulk outward motion to liquid shielding and quantitatively determined the magnitude of that motion. Further, he has shown that this effect will be reduced by 70% for a segmented annular array due to dissipation by viscous forces [5]. The induced speed from neutrons is then

$$v_n = \frac{0.3 \cdot E_n \cdot \Gamma}{C \cdot m},$$

where (E_n) is the total deposited neutron energy, (Γ) is the Gruneisen constant, (C) the liquid sound speed, and (m) the total amount of mass in the shielding curtain.

V. Effects of Parameter Variation

The final averaged outward liquid speed (v) is then the sum of the velocities induced by the mechanisms described above:

$$v = v_a + v_v + v_n.$$

Fig. 3 is a normalized plot showing how variation of several key reactor parameters affects the magnitude of this total outward velocity with respect to the baseline Z-IFE reactor design.

VI. Resutls for Z-IFE

The baseline Z-IFE reactor design assumes a 3 GJ target yield with approximately 50 cm of flibe shielding the first-wall. A more aggressive design calls for 4.7 GJ target yields and a reduction in the number of reactors by going to higher repetion rates. To handle the increased neutron fluence, the shielding thickness is increased to 1 m. Table 1 summarizes the outward liquid velocities induced for both of these designs. It is important to note that higher velocities are achieved in the lower yield baseline case due to the reduced curtain thickness.

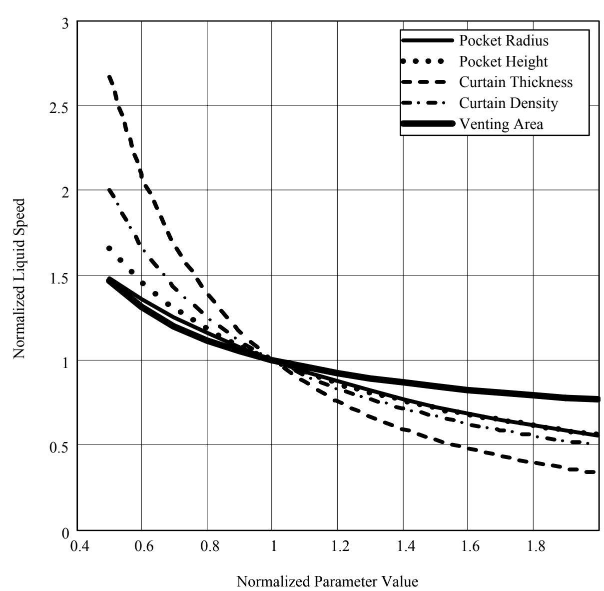

Figure 3. A plot showing how outward liquid velocity varies with various parameters normalized to the baseline Z-IFE reactor design.

TABLE I. SUMMARY OF OUTWARD LIQUID VELOCITES FOR Z-IFE

	Z-IFE Plant Design	
Effect	***3 GJ***	***4.7 GJ***
Ablation	0.7 m/s	0.4 m/s
Pocket Venting	2.8 m/s	1.8 m/s
Neutron Isochoric Heating	2.7 m/s	1.8 m/s
Total	6.2 m/s	4 m/s

VII. SUMMARY AND CONCLUSIONS

The average outward velocity of liquid in a Z-IFE reactor due to x-ray ablation, pocket venting, and neutron isochoric heating has been calculated. With knowledge of the fall speed of the liquid curtain, the results of these calculations can be used to determine the nominal deflection angle the curtain will have after a fusion explosion. The reactor first-wall can then be flared appropriately to avoid direct bulk liquid impact and the wall stresses that would result.

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